Testing the accuracy of feldspar single grains to date late Holocene cyclone and tsunami deposits

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Abstract: Quartz is the preferred dosimeter for luminescence dating of Holocene sediments as optically stimulated luminescence (OSL) signals reset rapidly upon light exposure, and are stable over time. However, feldspar is required where quartz luminescence properties are inappropriate for dating, as is often the case in geologically young mountain ranges and areas with young volcanism. Here we aim to evaluate the potential of single grain feldspar luminescence dating applied to late Holocene cyclone and tsunami deposits, for which complete signal resetting can *a priori* not be guaranteed. To address potential problems of feldspar dating of such deposits associated with heterogeneous bleaching, remnant doses and anomalous fading, we use a low-temperature post infrared infrared stimulated luminescence protocol ($pIRIR_{150}$) on single grains.

For most samples, good agreement between fading corrected IR_{50} and non-fading corrected $pIRIR_{150}$ ages is observed. Both feldspar ages generally also show good agreement with age control provided by historical data and quartz luminescence ages. $pIRIR_{150}$ remnant ages in modern analogue samples are shown to be <50 years, indicating that dating accuracy might be negatively affected by insufficient signal zeroing only for sediments younger than ~500 years. As these minor remnant ages are interpreted as being caused by unbleachable luminescence residuals, slight age overestimation for young samples can be overcome by subtracting the remnant ages.

The good agreement between $pIRIR_{150}$, IR_{50} and quartz ages, indicates that a significant number of grains must have experienced relatively complete signal resetting during or immediately prior to transport, as the three signals are known to bleach at different rates. Since light exposure during the event is expected to be limited, we deduce that a significant portion of the grains in the cyclone and tsunami deposits was already bleached prior to the event of interest. These well-bleached grains were likely eroded the beach, while other grains with larger remnant ages probably originate from the shallow subtidal, coastal barriers or even further inland sources. Additional signal resetting during storm and tsunami transport is indicated by slightly younger quartz than feldspar ages for grains with incomplete pre-transport resetting that were eroded at the Holocene coastal barrier.

Keywords: single grain dating; feldspar dating; post infrared infrared stimulated luminescence; tsunami deposit; cyclone deposit; transport processes

1. Introduction

Flooding by tsunamis and tropical cyclones (TCs) poses a major risk for low-lying and densely populated coastal areas worldwide. Since instrumental and historical records of tsunamis and TCs are often limited to a few decades or centuries (Sugawara et al., 2008; May et al., 2013) – time periods usually too short to predict long-term variations of TC activity (Donnelly and Woodruff, 2007) or the recurrence intervals of large tsunamis (Cisternas et al., 2005) – interpreting sedimentary onshore evidence is crucial for reconstructing long-term magnitude-frequency patterns of coastal flooding events. This requires chronological information on identified event deposits. While the use of radiocarbon and U/Th dating is often impeded by reworking or the absence of datable material (May et al., 2015), optically stimulated luminescence (OSL) dating is more widely applicable.

If applied to sediments of mid- to late Holocene age, quartz is typically the preferred dosimeter for OSL dating. Given the presence of a dominant fast component (cf. Jain et al., 2003), which is usually stable at ambient temperature and easier to reset than feldspar signals (e.g. Wintle, 2008) this enables successful dating of sediments as young as a few years using quartz OSL (Ballarini et al., 2003; Madsen et al., 2005). Unfortunately, tsunamis are particularly frequent in areas with poor quartz properties (cf. Tsukamoto et al., 2003). The majority is triggered by submarine earthquakes along geologically young subduction zones associated with volcanism, such as in Japan, Chile or Indonesia. Likewise, volcanic island arcs such as the Philippines and Japan are among the most TC affected regions worldwide. In these regions, minerals typically originate from freshly eroded plutonic, metamorphic or volcanic bedrock and thus experienced a restricted number of transportation cycles. In consequence, quartz is often affected by dim luminescence signals (Lukas et al., 2007) and significant contributions of unstable signal components (Preusser et al., 2006; Steffen et al., 2009).

As an alternative, optical dating of feldspar may give insights into the long-term frequency of tsunamis and TCs in such regions (e.g. Huntley and Clague, 1996; Riedesel et al., 2018). However, feldspar luminescence signals show slower resetting by sunlight compared to quartz OSL. Significant signals that were not bleached in nature (remnant doses) may remain even after prolonged light exposure (Yi et al., 2016). In environments prone to light exposure during sediment transport, feldspar signals measured with a conventional infrared stimulated single aliquot regenerative dose (SAR) protocol at 50 °C (IR_{50}) have been proven to bleach sufficiently well to be useful even for very young deposits (e.g. Gaar et al., 2013). However, incomplete signal resetting is assumed to be challenging for dating tsunami and TC deposits which are usually transported under turbulent flow conditions, over short distances, and sometimes even at night (e.g. Jaffe et al., 2012). In particular for young deposits with ages of only a few hundred years or less, the remnant doses of feldspar may be large compared to the relatively low natural doses accumulated since deposition (Reimann et al., 2011; Reimann and Tsukamoto, 2012). Moreover, signal loss due to anomalous fading may cause large age underestimation in feldspar dating (Huntley and Lamothe, 2001). Fading correction is possible, but may be related to large uncertainties and/or inaccuracies (Wallinga et al., 2007; Trauerstein et al., 2012).

Age underestimation due to fading in feldspar can be avoided or at least significantly reduced by using more stable post-infrared infrared (pIRIR) signals (Thomsen et al., 2008; Buylaert et al., 2012). Unfortunately, the most stable pIRIR signals measured at high temperatures >200 °C (i.e. $pIRIR_{225}$ and $pIRIR_{290}$) are usually much harder to bleach than the IR_{50} signal and may suffer from large residual doses of several Gy (Kars et al., 2014). This impedes accurate dating of Holocene deposits, particularly if they are incompletely bleached. Residual doses can be reduced by means of pIRIR signals measured at lower temperatures (below ~200 °C) that are easier to reset and often still not significantly affected by fading (Reimann et al., 2011; Fu and Li, 2013). Well-bleached and incompletely bleached feldspar grains may be separated using single grain measurements (Reimann et al., 2012).

The combination of low-temperature pIRIR protocols with single grain measurements offers the potential to isolate low or non-fading feldspar signals that are sufficiently bleached to enable dating of young and incompletely bleached TC and tsunami deposits. By overcoming some of the main drawbacks related to quartz dating of coastal flooding deposits, which are often accumulated in stratigraphically complex near-shore archives affected by water table variations, these feldspar signals may even be advantageous to those of quartz with adequate luminescence properties. In case of storm sediments composed of mixtures of coral rubble, shell hash, and sand-sized quartz and feldspar, for example, external dose rates are hard to reconstruct (Brill et al., 2017). The higher internal dose rate of potassium feldspar can reduce the uncertainties of dosimetry assessment (Davids et al., 2010).

This study aims to evaluate the potential of feldspar luminescence dating to reconstruct late Holocene coastal flooding events younger than 3000 years. For this, we apply single grain dating of sand-sized potassium feldspar using both conventional IR_{50} and low-temperature pIRIR signals to TC and tsunami deposits from Northwest Australia, Southwest Thailand, East Japan, and the Central Philippines. We compare the resulting feldspar ages with independent age control in the form of quartz OSL ages, radiocarbon data, and regional records of historical tsunami and TC impacts to test the completeness of signal resetting and the robustness of fading correction. Finally, the degree of resetting of feldspar signals is used to infer information on the sources and the transport conditions of sediments within tsunami and TC waves.

2. Material and Methods

2.1 Tsunami and cyclone deposits dated in this study

The tsunami and TC deposits investigated in this study originate from four different regions (Fig. 1a): Eastern Japan (JSH, 3 samples), the Central Philippines (TOL, 2 samples), Southwest Thailand (KPT, 2 samples), and Northwest Australia (PLY, 16 samples). Selection criteria were the existence of robust age control in form of quartz luminescence ages, radiocarbon ages, and/or historical records, as well as deposition less than 3000 years ago.

Two samples were collected from sand sheets in marsh deposits of the Shirasuka lowlands, Japan (Fig. 1b). The discontinuous sand layers are interpreted to reflect sedimentation during tsunami and/or typhoon inundation within the last 1000 years (Komatsubara et al., 2008). Samples for luminescence dating were taken from a sediment drill core described in detail by Garrett et al. (2018). Since quartz turned out to have inappropriate luminescence properties (Riedesel et al., 2018), optical dating of tsunami and typhoon recurrence had to be based on feldspar. Here we use sand layers at core depths of 120 cm (JSH 1-7) and 230 cm (JSH 1-18), for which radiocarbon dating yields ages younger than 1000 cal years BP (Garrett et al., 2018). Correlation with the stratigraphy described by Komatsubara et al. (2008) points to deposition by the AD 1605 Keichō tsunami and the AD 1361 Shōhei tsunami, respectively. As a modern analogue for the best-bleached sediment source of the investigated tsunami deposits, a sample was collected at the modern beach (JSH mod).

In the Philippines, two samples for feldspar dating were collected from sandy onshore deposits of the 2013 Typhoon Haiyan that were accumulated in a back-barrier marsh near Tolosa, northern Leyte (Fig. 1d). Samples for feldspar dating originate from a suspension-settled sand sheet (TOL 8), deposited during the inundation of the back-barrier marsh by the storm surge, and from a laminated washover unit (TOL 5, Fig. 1e) formed by swash-dominated flooding (Brill et al., 2016). Due to very dim luminescence signals not dominated by the OSL fast component (Fig. S1 in the supplement), comparison of feldspar data with quartz OSL ages is not possible.

In Thailand, two samples were taken from tsunami-laid sand sheets deposited during the last 3000 years and archived in the swales of a beach-ridge plain on Phra Thong Island (Jankaew et al., 2008; Brill et al., 2012a; Fig. 1f). One sample was dated from deposits of the 2004 Indian Ocean Tsunami (KPT 2). Another sample originates from a palaeotsunami deposit (KPT 20) that was dated to 550 years using radiocarbon dating (Jankaew et al., 2008) and quartz OSL (Brill et al., 2012a, b). This points to deposition by a tsunami triggered by a Sunda Arc rupture at about AD 1450 (Meltzner et al., 2010).

Finally, a total of 15 samples were dated from TC deposits forming washover fans at the south-eastern margin of the Exmouth Gulf, Northwest Australia (Fig. 1h). The washover fans are composed of successions of sandy TC deposition separated by palaeosols (Fig. 1i), which are interpreted to reflect phases of varying TC activity within the last 3000 years (May et al., 2017). Samples for feldspar dating were collected from sandy TC deposits at trenches PLY 8 (3 samples), PLY 16 (3 samples), PLY 19 (4 samples) and PLY 25 (5 samples). Age control is available in form of single grain quartz OSL ages, which indicate relatively well-bleached sediments affected by micro-dosimetry and sediment mixing during transport, and, therefore, were calculated using the central age model (CAM; Galbraith et al., 1999) and the finite mixture model (FMM; Galbraith and Green, 1990), respectively (Brill et al., 2017). As a modern analogue, a modern beach sample (PLY 18) that is assumed to reflect the best-bleached sediment source of local TC deposits was collected.

2.2 Sample preparation and instrumentation

Samples for dating were collected from trenches using steel cylinders at PLY, KPT and TOL, or from opaque plastic drill cores split in the laboratory in case of JSH. Subsequently, samples for palaeodose determination were pre-processed under dimmed red light in the Cologne Luminescence Laboratory (CLL) using standard procedures to separate coarse grain potassium feldspar. This included sieving to fractions of 100-200 µm or 150-200 µm, chemical treatment with HCl (10%), H_2O_2 (10%) and sodium oxalate to remove carbonates, organics and clay, as well as density separation to extract potassium-rich feldspar (<2.58 g/cm³). Samples for dose rate determination were dried to determine in-situ water contents. Uranium, thorium and potassium concentrations were assessed by means of high-resolution gamma spectrometry at the CLL and the VKTA – Strahlenschutz, Analytik & Entsorgung Rossendorf e. V. (Tab. S1 in the online supplement). To account for the reduced efficiency of alpha particles in generating IRSL signals, a-values of 0.15±0.05 are adopted from Balescu and Lamothe (1994). Beta counting conducted at the Aberystwyth luminescence laboratory was used to estimate the bulk internal potassium contents of feldspar extracts from all sites. The results suggest that adopting the value of 10±2% determined by Smedley et al. (2012) is appropriate for our samples. For more details concerning sample collection at the individual sites see also Brill et al. (2012a, b) for KPT, Brill et al. (2016) for TOL, Riedesel et al. (2018) for JSH, and Brill et al. (2017) for PLY.

Potassium feldspar grains were measured on single grain discs with hole diameters of 300 µm at the Wageningen luminescence laboratory to perform equivalent dose (D_e) measurements, residual dose determination, dose recovery tests, and fading experiments for all samples. Single grain discs of all samples were randomly checked for the number of grains in each hole under the microscope. More than a single grain was observed very rarely. Only for protocol validation and additional fading experiments, 1 mm-diameter aliquots mounted on steel discs using silicon oil were used. All measurements were carried out on automated Risø TL/OSL readers equipped with $^{90}Sr/^{90}Y$ beta sources delivering 0.11-0.13 Gy/s at the hole position. Signals were stimulated by an IR laser centred at 830 nm in case of single grains, and an array of IR LEDs (870±40 nm) for the 1 mm aliquots. All feldspar signals were separated from stimulation light using an interference filter with peak transmission at 410 nm.

The measurements followed a modified version of the pIRIR protocol proposed by Thomsen et al. (2008) (details are provided in section 3.1). The signals for D_e determination were derived by subtracting a background estimated from the last 20 s of the decay curve from the first 4 s of the decay curve in case of multi grain aliquots, and the last 0.33 s from the first 0.2 s of the decay curve for single grains. All measured grains and aliquots that passed the rejection criteria in terms of recycling ratio (0.85-1.15) and recuperation (0.2 Gy for IR_{50} and 0.4 Gy for $pIRIR_{150}$ signals, i.e. 5% or 10% of the largest regenerative dose) were considered for palaeodose estimation. In terms of relative recuperation (in % of the natural dose), the thresholds of 0.2 and 0.4 Gy used in this study are larger than those adopted in most other studies (e.g. Smedley et al., 2016), but we demonstrate that this has no effect on the palaeodose (see section 3.2). To calculate palaeodoses we applied the bootstrapped minimum age model (MAM_{bs}; Cunningham and Wallinga, 2012) (for details on age model selection see section 3.5). $Sigma_b$ values (σ_b) of 0.40±0.05 (PLY, JSH) and 0.35±0.05 (KPT) are based on the smallest over-dispersion of each sample set as the best estimate for the over-dispersion of a well-bleached sample (see section 3.4). Age calculation was performed with the Adele software (Kulig, 2005). Finally, samples with g-values larger than 1 %/decade (i.e. mainly the IR_{50} ages) were fading corrected using the approach of Huntley and Lamothe (2001). G-values <1 %/decade (all $pIRIR_{150}$ ages) are assumed to be laboratory artefacts and not corrected for, following Buylaert et al. (2012).

3. Results and interpretation

3.1 Selection of a pIRIR protocol

On the basis of 1 mm aliquots from one of the Australian samples (PLY 25-3), a series of preheat experiments were performed to select the ideal combination of thermal treatments. We tested pIRIR measurement temperatures between 110 and 290 °C, where the preheat temperature was always 25 °C above the corresponding pIRIR temperature. It can be observed that the natural doses form a constant dose plateau for pIRIR temperatures ≥150 °C (Fig. 2a), indicating insignificant fading (this assumption is supported by low g-values <1 %/decade, see section 3.2). At the same time, residual doses after 24 h of solar simulator bleaching remain below 0.1 Gy for pIRIR temperatures of 110-180 °C, while they increase significantly for higher temperatures (Fig. 2b). Finally, laboratory doses applied after 24 h of solar simulator bleaching are successfully recovered within ±10 % for pIRIR temperatures of 110-290 °C, if corrected for their residual doses (Fig. 2c). However, given the large residuals for pIRIR temperatures >200 °C, the uncertainties increase significantly for this temperature range. A pIRIR temperature of 150 °C provides a reasonable compromise between low residual doses and signal stability (shaded area in Fig. 2). Hence, all further measurements follow a pIRIR protocol with stimulation at 150 °C, a preheat at 175 °C for 10 s, and an IR bleaching at 190 °C for 100 s at the end of each SAR cycle ($pIRIR_{150}$ protocol in Tab. 1). Test doses are kept constant at ~5 Gy, and each sequence includes measuring 2-4 regenerative doses, the repeated first regenerative dose (recycling ratio), and a zero dose (recuperation). This protocol selection is backed by preheat experiments performed on the Japanese samples (Riedesel et al., 2018). For the samples from Thailand and the Philippines dose recovery ratios of 1.0±0.04 and 0.9±0.05 measured on samples KPT 2 and TOL 8, respectively, indicate the validity of the $pIRIR_{150}$ protocol.

Multi grain aliquots (1 mm) of sample PLY 25-3 are further used to evaluate the comparability of IR_{50} signals as part of the selected $pIRIR_{150}$ protocol, with those measured by means of a standard IR_{50} SAR protocol (see Tab. 1 for protocol details). Mean equivalent doses of 1.53±0.05 Gy (conventional IR_{50}) and 1.54±0.05 Gy (IR_{50} measured in $pIRIR_{150}$ protocol) are identical within 1-σ errors. This indicates that the IR_{50} signal measured within the applied $pIRIR_{150}$ protocol can be used as a substitute for conventionally measured IR_{50} signals. Consequently, both signals measured within the $pIRIR_{150}$ protocol are considered when deriving ages for the tsunami and TC deposits.

3.2 Feldspar luminescence properties

Both IR_{50} and $pIRIR_{150}$ are characterised by sufficiently bright signals for single feldspar grains from PLY, KPT, and JSH (at least several 100 counts for ~5 Gy test doses of accepted grains; Fig. 3a). Between 31% (JSH) and 53% (KPT) of the grains provide 90% of the cumulative IR_{50} and $pIRIR_{150}$ signals (Fig. 3c). A total of 46-68% (IR_{50}) and 31-56% ($pIRIR_{150}$) of the grains pass the rejection criteria. The $pIRIR_{150}$ signals show no significant fading at all three locations, regardless if measured on single grains or 1 mm aliquots (g-values of 0.2±0.3 to 0.7±0.4 %/decade; Fig. 3a). The IR_{50} signals yield larger g-values suggesting that fading correction is required. Multi grain aliquots (3 aliquots per sample) indicate g-values of 1.5±0.3 %/decade at KPT, 3.0±0.3 %/decade at PLY and 2.8±0.4 %/decade JSH. Single grain data show extremely large scatter and suggest higher mean g-values of 5-8 %/decade at PLY and JSH, and lower ones around zero at KPT (Fig. 3a).

Feldspar from the Philippines (TOL), on the other hand, is completely insensitive to IR stimulation. No significant IR_{50} and $pIRIR_{150}$ signals were recorded after measuring ~200 grains (Fig. 3a). At the same time, beta counting points to very low potassium contents of only ~1.5% for bulk feldspar samples from this site, while the respective potassium concentrations of feldspar extracts from all other locations exceed 7%. Feldspar extracts from TOL, thus, seem to contain no significant amounts of potassium feldspar and are not further considered in this study.

To test the sensitivity of dose determination towards variations of the selected rejection criteria, mean equivalent doses based on a successively increasing number of grains are plotted (Fig. 3d). The grains are ordered with regard to the difference between recycling ratio and unity (from good = recycling ratios of 1, to poor = recycling ratios of 0.85 or 1.15) and recuperation (from low to high recuperation doses) (cf. Thomsen et al., 2016; Fig. 3d). Within the defined acceptance limits, no dependency on recycling ratios is observed for all measured samples. Likewise, rejection of additional grains due to recuperation by successively tightening the initial acceptance criteria of 0.2 Gy (IR_{50}) and 0.4 Gy ($pIRIR_{150}$) does not lead to systematic changes of the final palaeodose. The rejection of further grains due to recuperation relative to their natural doses would lead to biasing towards older grains (by systematically excluding lower D_e values; Fig. S2a online supplement) and was not conducted. Instead the dose response curve was forced through the origin for all samples.

3.3 Over-dispersion in dose recovery tests

To collect information on the dose scatter of well-bleached samples from each site that were not object to significant dose rate heterogeneity during burial, the over-dispersion values of dose recovery experiments are determined using the CAM. For this, β-doses of ~5 Gy are applied to (i) samples artificially bleached in a solar simulator for 24 h (PLY 18, KPT 2, JSH 1-7); and (ii) samples of presumably modern age – and therefore assumed to have insignificant remnant doses compared to the 5 Gy laboratory dose – from the modern beach (PLY 18, JSH mod) and the 2004 Indian Ocean Tsunami (KPT 2). While the $pIRIR_{150}$ and IR_{50} over-dispersions are similar for individual locations, the over-dispersion values of modern samples are slightly larger than those of artificially bleached samples in case of both IR_{50} signals (13-15% compared to 8-13%) and $pIRIR_{150}$ signals (12-16% compared to 9-13%) at all sites (Fig. 4a). This suggests that apparently not all grains in the natural reference samples have been completely bleached prior to their last deposition, especially the 2004 tsunami deposit from KPT. Thus, part of the over-dispersion is caused by heterogeneous luminescence signal resetting of the grains (see also section 3.4). The dose-recovery ratios support this assumption. Those of modern samples show only appropriate ratios between 0.9 and 1.1 if the natural remnant doses are subtracted (dose-recovery ratios of 0.98-1.03 instead of 0.99-1.12). The dose-recovery ratios of artificially reset samples are acceptable without any correction (0.95-1.02). However, the differences between sites and signals are small compared to the dose scatter of natural D_e distributions (see section 3.5). Over-dispersion values of 8-16% for both signals are therefore a reasonable estimate for the internal scatter caused by experimental uncertainties for all dated samples.

3.4 Natural remnant doses and laboratory residuals

For the same samples that have been analysed for equivalent dose scatter in dose recovery tests (section 3.3), the IR_{50} and $pIRIR_{150}$ signals after resetting in nature (remnant doses of modern sediments) and those of samples artificially bleached in a solar simulator (residual doses) are determined. Residual doses allow for the estimation of charge transfer to the natural luminescence signal during the measurement procedure and should, thus, be considered when interpreting the dating accuracy of samples with unknown age. The equivalent dose of modern analogues provide information on the degree of signal resetting in nature, and may be used to correct feldspar ages by subtracting these natural remnant doses (e.g. Ollerhead and Huntley, 2011; Kars et al., 2014).

Residual doses that remain after signal resetting in the laboratory – as the result of thermal transfer and/or re-trapping of charge – were calculated using the CAM, because bleaching in the solar simulator zeroed all grains more or less homogeneously. Values vary between 0.01-0.04 Gy (PLY and KPT) and 0.14 Gy (JSH) in case of IR_{50} signals, and between 0.05 Gy (PLY) and 0.3-0.4 Gy (KPT and JSH) in case of $pIRIR_{150}$ signals (Fig. 4b). While these laboratory residuals are insignificant for the equivalent doses of most samples from PLY and KPT, they account for up to 20% of the equivalent doses in case of JSH.

The D_e distributions of the 2004 tsunami deposit and the modern beach samples from Japan and Australia (i.e. the modern analogues) show indication of partial bleaching. All these samples are mixtures of well-bleached grains with low equivalent doses, and insufficiently bleached grains with larger equivalent doses (see Fig. S5 in the supplement). Since dating of samples with unknown age in this study is only based on the best-bleached grains of each sample, corresponding natural remnant doses should be estimated from the best-bleached grains of the modern analogues only. To extract the palaeodose of these best-bleached grains we use the MAM_{bs}. Crucial for its application is the estimation of a robust σ_b value. In absence of non-modern, well-bleached sediments, σ_b is derived by using the smallest over-dispersion from each sample set as the best estimate for that of a well-bleached sample. The obtained σ_b values are 0.40±0.05 (PLY, JSH) and 0.35±0.05 (KPT) for both the IR_{50} and $pIRIR_{150}$ data sets (Fig. 5). Similarly large σ_b values (up to 0.50) have been reported for IR_{50} and pIRIR single grain equivalent dose distributions of well-bleached feldspar samples from glacial settings (Smedley et al., 2016). Given the composition of the deposits used in this study (a few feldspar grains embedded in mixtures of quartz sand and carbonates), values in the range of 0.30-0.45 are assumed to be realistic.

The calculated natural remnant doses of the best-bleached feldspar grains vary between 0.025±0.01 Gy (PLY 18) and 0.07±0.02 Gy (KPT 2) for IR_{50} signals, and between 0.035±0.02 Gy (PLY 18) and 0.19±0.03 Gy (JSH mod) for $pIRIR_{150}$ signals (IR_{50} and $pIRIR_{150}$ nat in Fig. 4b). The lack of significant differences between laboratory residuals and natural remnant doses suggests that at least for the best-bleached grains both IR_{50} and $pIRIR_{150}$ signals have been well reset in nature. We calculated remnant ages for all modern analogue samples by considering remnant doses, dose rates, multiple grain g-values (only for IR_{50}) and the corresponding age control (i.e. by subtracting the time difference between deposition and sample collection). The natural remnant ages of all three samples vary between 0 and 27 years for the IR_{50} signal (KPT = 0 years, JSH = 19 years, PLY –=27 years) and 2 and 48 years for the $pIRIR_{150}$ signal (KPT = 2 years, JSH = 48 years, PLY = 36 years; Tab. 2). These remnant ages are astonishingly small compared to previously published data, especially for the $pIRIR_{150}$ signal (e.g. Reimann et al., 2012). Interestingly, two of the $pIRIR_{150}$ remnant ages agree with their fading-corrected IR_{50} counterparts within 2-σ uncertainties. For the third one (JSH mod), the $pIRIR_{150}$ remnant age is only slightly older than the IR_{50} age within 2-σ. Since both signals bleach at different rates, a significant percentage of grains in these samples may have experienced significant light exposure during or prior to transport (Reimann et al., 2015). The measured remnant doses rather seem to reflect unbleachable residuals (particularly since laboratory residuals have approximately the same size) and should be subtracted from the feldspar ages of palaeosamples to improve dating accuracy (e.g. Ollerhead and Huntley, 2011; Kars et al., 2014). The source of these residuals may be competition between signal resetting and retrapping at low dose levels during light exposure (Ollerhead and Huntley, 2011), or a dose-dependent charge carry-over effect from regenerative dose cycles to the adjacent test dose cycles (Colarossi et al., 2018; Riedesel et al., 2018).

The observation of complete bleaching at the 2-σ level (a grain is classified as completely bleached when its dose overlaps with the expected dose of the sample within 2-σ errors) applies to nearly 100% of the grains in case of modern beach deposits from PLY 18 (Fig. S5). In case of the 2004 tsunami deposits from Thailand (KPT 2) only ~40% of the grains are well-bleached. The modern beach sand from JSH mod yields ~70% of well-bleached grains for the IR_{50} signal. But only ~15% of the grains yield well-bleached $pIRIR_{150}$ signals.

3.5 Palaeodose and age calculation for tsunami and cyclone deposits

All data relevant for palaeodose and age calculation are summarised in Table 2. For D_e datasets of both signals, very similar over-dispersion values of 35-155% (IR_{50}) and 34-143% ($pIRIR_{150}$) are observed. The majority of the samples from all three sites show unimodal distributions with moderate to large over-dispersion between 35 and 110% (Fig. 6a, b, d). Only some samples from the Australian site (PLY 8-1, 2; 16-1-3; 19-1, 2) are characterised by bimodal D_e distributions with larger over-dispersion values of 70-155% (Fig. 6c).

Since at least some of the over-dispersion is interpreted to reflect incomplete bleaching, the MAM_{bs} was applied to estimate burial doses for all samples. For appropriately selected σ_b values (particularly since applied with an uncertainty, in this study 0.35±0.05 and 0.40±0.05), the MAM_{bs} should also be adequate for well-bleached deposits (Fig. 5b; Chamberlain et al., 2018). This should also be valid for samples with bimodal D_e distributions (as shown in Fig. 6c). These distributions most likely reflect mixing of different sediment sources during TC and tsunami transport and not post-depositional mixing (see also section 4.2.). Thus, the grain population with the lower equivalent doses, which is dated by the MAM_{bs}, reflects the more recently bleached and therefore younger sediment source (i.e. the best-bleached grains) for all corresponding samples.

The $pIRIR_{150}$ ages and the IR_{50} ages from KPT are not corrected for fading, because all measurements indicate supposedly insignificant g-values <1 %/decade (cf. Buylaert et al., 2012). The IR_{50} ages from PLY and JSH, on the other hand, are fading corrected. Since 1 mm aliquots and single grains indicate different g-values at all sites, fading corrected ages using both g-values are presented at this stage (Tab. 2). Eventually, all feldspar ages are corrected by subtracting the remnant ages determined for modern analogue samples.

4. Discussion

4.1 Comparison of single grain feldspar ages with age control

To test the validity of the luminescence age estimates, we compare the dating results obtained using the different signals with each other and with independent age control. When results of different luminescence signals are compared, we need to take into account that these methods are not entirely independent, as they are partly based on the same measurements and assumptions; e.g. the external dose rate is the same, as well as beta-dose rate calibration. To avoid overinterpretation of our data, we eliminate all shared errors prior to comparing IR_{50}, $pIRIR_{150}$ and quartz ages (i.e. 3.5% machine reproducibility on single grain D_e determination, uncertainties on external gamma and beta radiation). In case of most samples investigated in this study, a good agreement between IR_{50} ages corrected for fading using multi grain g-values and $pIRIR_{150}$ ages not corrected for fading (both after subtraction of remnant doses) is observed (Fig. 7a). Even for samples younger than 800 years, $pIRIR_{150}$ and IR_{50} ages agree at the 1-σ level (Fig. 7b). Likewise, both IR_{50} and $pIRIR_{150}$ feldspar ages generally match historical records and quartz ages for all samples within 2-σ errors (Fig. 7c, d, f, g). Even at the 1-σ confidence level, the majority of the samples agree with age control. Notable exceptions are the $pIRIR_{150}$ and IR_{50} ages older than 2000 years (PLY 25-1, 25-2, 19-4), which show a systematic trend of underestimating the age control (Fig. 7c, f).

If the single grain g-values of 5.0±0.8% (JSH) and 6.7±0.8% (PLY) are used, fading corrected IR_{50} ages tend to overestimate both $pIRIR_{150}$ ages and age control (Fig. S6). Similar trends towards over-correction of young feldspar samples when applying g-values >5% were already reported by Reimann et al. (2011). The reason for the erroneously large single grain g-values of our samples is not yet clear, presumably related to a bias in the large scatter of the measured single grain g-values (Fig. S4). Therefore, we use multi-grain g-values to fading correct IR_{50} ages in the following.

The general agreement with age control for very young samples of only a few centuries is in line with the low IR_{50} and $pIRIR_{150}$ remnant doses measured on the best-bleached feldspar grains of modern analogues from Thailand (KPT) and Australia (PLY). These indicate more or less complete signal resetting at the time of deposition. At both sites, the feldspar remnant ages of 0-36 years agree within 1-σ uncertainties with those of quartz reported for the same sites (15-25 years; Brill et al., 2012a, 2017). They are also well in the range of quartz remnant ages reported for tsunami (e.g. Eipert, 2004; Murari et al., 2007), storm (e.g. Cunningham et al., 2011; May et al., 2015) and beach deposits (e.g. Armitage et al., 2006) elsewhere. Slightly larger remnant ages of ~50 years for the $pIRIR_{150}$ signals were obtained using the best-bleached grains of modern beach deposits from JSH. However, after remnant dose subtraction (see section 3.4.) the Japanese samples (JSH 1-7 and JSH 1-18) agree with age control as well.

While discussing potential reasons for slightly over- or underestimating the age control at the 1-σ confidence level, it should also be taken into account that the systematic discrepancies observed for samples older than 2000 years from PLY could also be an issue of inaccurate quartz ages. Differences might at least partly result from the different age models used for quartz and feldspar dating. While the use of the MAM_{bs} is in line with the age model selection for published quartz ages at KPT (Brill et al., 2012a), different age models were used for the quartz ages at PLY (Brill et al., 2017). The quartz dose distributions at PLY show the same patterns as the respective feldspar dose distributions described in this paper (section 3.5). But the authors argued (i) that the FMM should be used to deal with the distinct populations of bimodal dose distributions (Fig. 6c), since they may reflect sediment sources with different pre-transport resetting; and (ii) that the CAM should be used for all samples with unimodal dose distributions, since their over-dispersion values are rather assumed to reflect dose rate heterogeneity than partial bleaching (Brill et al., 2017).

The use of different age models despite the similarities of the quartz and feldspar dose distributions might explain the systematic discrepancies between both datasets observed for IR_{50} and $pIRIR_{150}$ ages older than 2000 years at PLY. It can be observed that bimodality of dose distributions due to mixing of sediment sources during transport tends to affect only the samples younger than 2000 years, while older samples show relatively broad unimodal peaks. This might point to increasing significance of the burial dose compared to the remnant doses and thus to overprinting of the pre-depositional grain populations by micro-dosimetry and other sources of D_e scatter. In this case, the application of the CAM might lead to a systematic overestimation of the quartz ages. The previously published quartz ages for these samples (Brill et al., 2017), which are based on the CAM, should therefore be interpreted as maximum ages. Since we assume the MAM_{bs} as the most appropriate age model in such settings, we also apply it to the quartz dose distributions of these samples to exclude any biasing of our conclusions by age model selection (Fig. 7e, h). As demonstrated in Figure 7e and 7h, any systematic offset between quartz and feldspar ages is successfully removed, when the MAM_{bs} is applied to both quartz and feldspar samples from PLY.

4.2 Implications for sediment sources and transportation processes in tsunami and cyclone waves

The good agreement between MAM_{bs}-based quartz, fading corrected IR_{50} and uncorrected $pIRIR_{150}$ ages – although all signals are known to bleach at different rates (Godfrey-Smith et al., 1988; Kars et al., 2014) – points to relatively complete signal resetting in the best-bleached grains of the investigated tsunami and TC deposits. Despite slight discrepancies of $pIRIR_{150}$ and fading corrected IR_{50} ages compared to the age control within 1-σ uncertainties for some samples, a systematic trend of age over-estimation due to less complete bleaching cannot be observed. These conclusions are, however, only true for the best-bleached grain population in each sample (i.e. the MAM_{bs} palaeodose). This applies to nearly 100% of the modern beach grains at PLY regardless of signal type (quartz, IR_{50} and $pIRIR_{150}$). But only ~40% (IR_{50} and $pIRIR_{150}$) and ~70% (quartz) of the 2004 tsunami grains from KPT are well bleached. At JSH, only 70% (IR_{50}) and 15% ($pIRIR_{150}$) of the grains from the modern beach yield well-bleached grains.

This well-bleached grain fraction reflects a sediment source with well reset signals prior to tsunami or TC transport, a phenomenon described as pre-bleaching. The littoral zone is the most likely source of these pre-bleached grains, since beach deposits are usually characterized by both well-bleached quartz signals (Armitage et al., 2006) and feldspar signals (Madsen et al., 2011). With feldspar remnant ages of only 27-36 years, sediments from the littoral zone at PLY clearly satisfy this requirement. Likewise, the slightly larger remnant ages of 19-48 years in beach deposits at JSH are in line with the reasonable agreement of IR_{50} and $pIRIR_{150}$ ages with age control if only the best-bleached grains are used for dating.

In addition to the well-bleached feldspar grains originating from the beach, grains or entire grain populations with ages significantly overestimating the age control are present in all samples. Modern tsunami deposits from Thailand reveal right-skewed D_e distributions indicating incomplete resetting of the luminescence signal in some grains eroded at the beach prior to deposition (Fig. 8a). With increasing age of the TC and tsunami deposits, the remnant ages of these incompletely bleached grains become rapidly insignificant and seem to reflect the beach as a single well-bleached sediment source (Fig. 8b). On the other hand, the bimodal D_e distributions observed for some PLY samples suggest mixing of pre-bleached grains from the beach with older grains. Considering the dimensions of the respective remnant doses calculated with the FMM (i.e. 2000-5000 years), the Holocene beach barrier is the most likely source of the older grains (Fig. 8c). The comparison of both grain populations reveals similar proportions for all three signals (i.e. ~65% of the grains in population 1 and ~35% in population 2). The peaks of the older grain population tend to shift towards younger ages for the more rapidly bleaching quartz signals compared to both feldspar signals (Fig. 8d). While the latter points towards the influence of signal resetting during sediment transport in tsunami and storm waves, the combination of a shifting peak position but unchanging proportion of the older grain population suggests that this resetting was rather limited due to transport under turbulent conditions.

5. Conclusions

Our investigations demonstrate that in general both IR_{50} and $pIRIR_{150}$ signals of a significant number of potassium feldspar grains are sufficiently reset to accurately date Holocene tsunami and tropical cyclone deposits with ages between 3000 years and 500 years from a variety of coastal settings. These best-bleached grains can be reliably extracted using the bootstrap Minimum Age Model. After subtraction of remnant ages obtained from modern analogue samples (in the order of 2-48 years), no significant age discrepancies at the 1-σ level compared to age control are observed even for sediments younger than 500 years. For samples older than 500 years, where residuals and remnant doses are insignificant compared to the natural dose of the best-bleached grain population, reasonable agreement at the 1-σ level was observed for both fading-uncorrected $pIRIR_{150}$ and fading-corrected IR_{50} ages, when using the bootstrapped minimum age model and without residual dose subtraction.

We argue that the reason for the good agreement between $pIRIR_{150}$ and IR_{50} feldspar ages and age control observed in this study is that a significant portion of the grains are derived from sediment sources sufficiently reset prior to transportation, most likely the beach. Additional, but rather limited resetting seems to take place during tsunami and cyclone transport. However, this is not the decisive factor for the low remnant ages of the best-bleached grains. These conclusions demonstrate the power of multiple luminescence signal datasets to inform not only on chronology, but also to provide valuable insights into earth-surface processes such as the sediment transport dynamics related to highly energetic cyclone and tsunami waves.

Acknowledgements

Financial support was kindly provided by the Deutsche Forschungsgemeinschaft (DFG) for sample collection in Australia (MA 5768/1-1) and Thailand (BR 877/27-1; BR 877/27-2), by the Faculty of Mathematics and Natural Sciences, University of Cologne (UoC), and a UoC postdoctoral grant (ZUK 81/1) for fieldwork in the Philippines, and by the Belgian Science Policy Office (BELSPO BRAIN-be BR121/A2) as part of the QuakeRecNankai project for sampling in Japan. SR acknowledges financial support by an AberDoc PhD scholarship. The research around Exmouth was kindly permitted and supported by Ann Preest, the local elders and aboriginal communities of Exmouth, and the Department of Environment and Conservation (Perth/Exmouth), as well as the owner and managers of Exmouth Gulf station. Hollie Wynne (Aberystwyth University, UK) is thanked for performing beta counting analysis for selected feldspar extracts from Japan, the Philippines and Australia.

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Figures and tables

Fig. 1: Study sites selected for feldspar single grain dating. a) Location of the four study sites Point Lefroy (PLY) in NW Australia, Phra Thong Island (KPT) in SW Thailand, Shiraska (JSH) in Japan, and Tolosa (TOL) in the Philippines (based on ESRI base maps). b) Shiraska lowlands with position of sediment core JSH 1 and the modern beach sample JSH mod (based on Google Earth/Digital Globe 11/10/2016). c) Stratigraphy of sediment core JSH 1. d) The coastal plain at Tolosa with positions of luminescence samples (based on Google Earth/Digital Globe 23/02/2012). e) The storm-typical planar lamination at TOL 5 sampled for luminescence dating. f) The beach-ridge plain on Phra Thong Island with locations of luminescence samples (based on Google Earth/Digital Globe 08/10/2015). g) Tsunami sand sheets sampled for luminescence dating in trench KPT 20. h) Supra-tidal back-barrier mudflat at Point Lefroy with locations of luminescence samples from washover fans (PLY 8,16,19,25) and the present beach (PLY 18) (based on Google Earth/Digital Globe 22/11/2014). i) Stratigraphy of the washover fan at PLY 25 with existing quartz OSL chronology (Brill et al., 2017).

Fig. 2: Protocol evaluation based on sample PLY 25-3. a) Preheat-plateau test with successively increasing pIRIR temperatures (110-290 °C) and preheat temperatures (always 25 °C higher than the pIRIR temperature). b) pIRIR residual doses after 24 hours of solar simulator bleaching for the same temperatures as used in (a). c) Residual corrected dose-recovery ratios for the same temperature range.

Fig. 3: Feldspar luminescence properties of the samples dated in this study. a) Feldspar single grain signals (IR_{50} and $pIRIR_{150}$) in response to ~5 Gy test doses for samples from PLY, KPT and TOL. Insert: Fading rates of sample PLY 25-3 shown as a boxplot. Open circles indicate outliers; vertical lines show the mean. b) Dose-response curves of feldspar samples in this study. While D_e determination is unproblematic for both signals and most samples (represented by JSH IR_{50}), some of the younger PLY samples (represented by PLY $pIRIR_{150}$) suffer from large recuperation, particularly in case of the $pIRIR_{150}$ signal. c) Representative light-sum curves for samples from PLY, KPT and JSH. d) Running average dose of accepted grains in order of the difference between recycling ratio and unity (from left unity, to right 15% difference) and recuperation (from left low, to right large).

Fig. 4: Over-dispersion in dose recovery tests, laboratory residuals and natural remnant doses measured on modern analogue samples. a) Over-dispersion of dose recovery tests with 5 Gy laboratory doses administered to modern age samples (PLY 18, KPT 2, JSH mod: squares) and solar simulator bleached samples (PLY 18, KPT 2, JSH 1-7: circles). b) Residual doses after 24 h of solar simulator bleaching and natural remnant doses of the same modern analogue samples without solar simulator resetting.

Fig. 5: Over-dispersion distributions for samples from PLY, JSH and KPT. For both, IR_{50} (a) and $pIRIR_{150}$ signals (b) the lowest values are in the range of 35% in case of KPT, and 40% in case of PLY and JSH.

Fig. 6: Equivalent dose distributions of selected samples from each locality shown as Abanico plots. (a) Thailand. (b) Japan (b), and Australia (c, d).

Fig. 7: Correlation of age control (historical data and quartz ages), fading corrected IR_{50} ages using multi-grain g-values, and fading-uncorrected $pIRIR_{150}$ ages (all corrected for natural remnant doses, i.e. the column "Age rc" in Table 2). a) IR_{50} ages plotted against $pIRIR_{150}$ ages. b) Zoom into the last 800 years (grey box in a). c) IR_{50} ages plotted against age control. d) Zoom into the last 800 years (grey box in c). e) IR_{50} ages plotted against age control but with quartz ages from PLY calculated with the MAM. f) $pIRIR_{150}$ ages plotted against age control. g) Zoom into the last 800 years (grey box in f). h) $pIRIR_{150}$ ages plotted against age control but with quartz ages from PLY calculated with the MAM.

Fig. 8: Indication for sediment sources and transport conditions of tsunami and cyclone deposits in single-grain data. While unimodal D_e distributions point to the beach as the only sediment source (a, b), bimodality of D_e distributions at PLY is explained by mixing of well-bleached beach sand with sediment from the mid- to late Holocene barrier (c). Incomplete bleaching of beach sediments can only be observed in very young event deposits (a). Besides that, the ages of the older grain population provided by different signals point to additional signal resetting during tsunami and cyclone transport (d). Compared to the more rapidly resetting quartz signals (older grain population indicated by peak at S2b), both IR_{50} and $pIRIR_{150}$ signals provide systematically older ages for grains derived from the barrier (peak at S2a).

a) pIRIR$_{150}$ protocol

Step	Treatment	Observed
1	Preheat (175 °C for 10s)	
2	IRSL (laser, 1.65s @ 50 °C)	L_x (IR_{50})
3	IRSL (laser, 1.65s @ 150 °C)	L_x ($pIRIR_{150}$)
4	Test dose	
5	Preheat (175 °C for 10s)	
6	IRSL (laser, 1.65s @ 50 °C)	T_x (IR_{50})
7	IRSL (laser, 1.65s @ 150 °C)	T_x ($pIRIR_{150}$)
8	IRSL (LEDs, 100s @ 190 °C)	
9	Dose (R1-R4, R0, RR)	
10	Return to step 1	

b) IR$_{50}$ protocol

Step	Treatment	Observed
1	Preheat (190 °C for 10s)	
2	IRSL (LEDs, 200s @ 50 °C)	Lx (IR_{50})
4	Test dose	
5	Preheat (190 °C for 10s)	
6	IRSL (LEDs, 200s @ 50 °C)	Tx (IR_{50})
8	IRSL (LEDs, 100s @ 220 °C)	
9	Dose (R1-R4, R0, RR)	
10	Return to step 1	

Tab. 1: The pIRIR$_{150}$ (a) and conventional IR$_{50}$ (b) protocols applied in this study. Note, in case of dose recovery experiments and determination of laboratory residuals, solar simulator bleaching for 24 h and application of a 5 Gy laboratory dose was performed prior to step 1. R1-R4 – regenerative doses, R0 – zero dose (for measurement of recuperation), RR – recycled dose (for measurement of recycling ratio).

Site	Sample	Signal	N_{ac}	**OD** (%)	σ_b	**Palaeodose** (Gy)	**Age unc.** (yrs)	**Age cor. SA** (yrs)	**Age cor. SG** (yrs)	**Age rc** (yrs)	**Age contr.** (yrs)
Thailand	KPT 2	IR_{50}	213	111±10	0.35±0.05	0.07±0.02	8±2	8±2	8±2	-	8*
		post-IR_{150}	147	88±9	0.35±0.05	0.10±0.02	10±6	10±6	10±6	-	
	KPT 20	IR_{50}	243	35±2	0.35±0.05	4.26±0.17	456±31	515±38	456±31	515±38	564*
		post-IR_{150}	242	34±2	0.35±0.05	5.25±0.18	546±35	546±35	546±35	544±35	
Japan	JSH 1-7	IR_{50}	103	40±3	0.40±0.05	1.35±0.09	336±31	413±41	494±65	394±41	410*
		post-IR_{150}	68	54±5	0.40±0.05	2.01±0.25	502±105	502±107	502±107	454±107	
	JSH 1-18	IR_{50}	122	38±5	0.40±0.05	1.59±0.06	486±41	601±56	722±93	582±56	650*
		post-IR_{150}	79	43±4	0.40±0.05	2.55±0.31	780±104	780±104	780±104	732±104	
	JSH mod	IR_{50}	230	-	0.40±0.05	0.06±0.02	16±5	19±6	24±8	-	0*
		post-IR_{150}	177	-	0.40±0.05	0.19±0.03	48±7	48±7	48±7	-	
Australia	PLY 8-1	IR_{50}	147	115±7	0.40±0.05	0.28±0.07	240±60	298±76	405±114	271±76	380±30**
		post-IR_{150}	83	109±9	0.40±0.05	0.50±0.05	426±56	426±56	426±56	390±56	
	PLY 8-2	IR_{50}	133	76±8	0.40±0.05	0.67±0.07	582±83	733±109	1020±197	705±109	922±51**
		post-IR_{150}	93	67±5	0.40±0.05	0.84±0.06	720±87	720±87	720±87	684±87	
	PLY 8-3	IR_{50}	143	44±3	0.40±0.05	1.39±0.16	910±140	1154±183	1627±332	1127±183	1362±57**
		post-IR_{150}	104	40±2	0.40±0.05	1.88±0.18	1238±171	1238±171	1238±171	1202±171	
	PLY 16-1	IR_{50}	114	128±10	0.40±0.05	0.15±0.03	114±28	140±35	186±52	113±35	130±10**
		post-IR_{150}	103	117±10	0.40±0.05	0.17±0.02	128±19	128±19	128±19	92±19	
	PLY 16-2	IR_{50}	171	105±6	0.40±0.05	0.23±0.03	178±26	220±33	296±54	193±33	204±12**
		post-IR_{150}	125	103±7	0.40±0.05	0.34±0.03	268±34	268±34	268±34	232±34	
	PLY 16-3	IR_{50}	177	93±6	0.40±0.05	0.22±0.04	144±31	178±39	237±59	151±39	206±14**
		post-IR_{150}	89	86±8	0.40±0.05	0.35±0.10	268±34	232±67	232±67	196±67	
	PLY 18	IR_{50}	108	-	0.40±0.05	0.02±0.01	22±4	27±5	39±9	-	0*
		post-IR_{150}	92	-	0.40±0.05	0.04±0.02	36±18	36±18	36±18	-	
	PLY 19-1	IR_{50}	268	155±16	0.40±0.05	0.23±0.02	172±23	213±30	286±50	184±30	342±33**
		post-IR_{150}	157	143±19	0.40±0.05	0.27±0.07	200±57	200±57	200±57	164±57	
	PLY 19-2	IR_{50}	205	126±13	0.40±0.05	0.58±0.03	498±54	626±71	867±140	599±71	788±75**
		post-IR_{150}	144	85±6	0.40±0.05	0.72±0.04	620±71	620±71	620±71	584±71	
	PLY 19-3	IR_{50}	181	53±3	0.40±0.05	1.09±0.06	898±101	1140±134	1605±275	1113±134	1284±66**
		post-IR_{150}	127	62±4	0.40±0.05	1.25±0.07	1026±116	1026±116	1026±116	990±116	
	PLY 19-4	IR_{50}	178	58±3	0.40±0.05	1.73±0.18	1390±201	1776±266	2536±517	1749±266	2264±101**
		post-IR_{150}	95	57±4	0.40±0.05	2.30±0.26	1844±277	1844±277	1844±277	1808±277	
	PLY 25-1	IR_{50}	154	43±3	0.40±0.05	2.66±0.09	1750±156	2243±215	3227±529	2216±215	2826±124**
		post-IR_{150}	101	37±3	0.40±0.05	3.66±0.14	2412±222	2412±222	2412±222	2376±222	
	PLY 25-2	IR_{50}	169	40±3	0.40±0.05	1.93±0.08	1222±127	1558±169	2216±374	1531±169	1956±87**
		post-IR_{150}	112	54±4	0.40±0.05	2.61±0.11	1654±173	1654±173	1654±173	1618±173	
	PLY 25-3	IR_{50}	250	39±2	0.40±0.05	1.49±0.04	948±83	1204±113	1699±262	1177±113	1230±83**
		post-IR_{150}	183	40±3	0.40±0.05	1.65±0.05	1046±92	1046±92	1046±92	1010±92	
	PLY 25-4	IR_{50}	176	41±3	0.40±0.05	0.79±0.04	622±64	785±85	1093±175	758±85	904±52**
		post-IR_{150}	95	44±4	0.40±0.05	0.88±0.06	690±80	690±80	690±80	654±80	
	PLY 25-5	IR_{50}	163	52±3	0.40±0.05	0.73±0.07	568±78	715±101	995±189	688±101	858±69**
		post-IR_{150}	104	47±4	0.40±0.05	0.95±0.06	742±85	742±85	742±85	706±85	

Tab. 2: Feldspar single-grain luminescence data for all samples measured in this study. N_{ac} - number of accepted grains, OD – over-dispersion, Age unc. – uncorrected ages, Age cor. SA – fading corrected ages using mean 1-mm diameter single aliquot g-values of 1.5±0.3% (KPT), 2.8±0.4% (JSH) and 3.0±0.3% (PLY) for the IR_{50} data, Age cor. SG – fading-corrected ages using mean single grain g-values of 5.0±0.8% (JSH) and 6.7±0.8% (PLY) for the IR_{50} data, Age rc – fading-corrected ages using multi-grain g-values after subtraction of remnant ages determined on

modern analogue samples (section 3.4. for details), Age contr. – age expected from age control (*historical record or modern, **quartz ages in Brill et al., 2017). All uncertainties provided reflect the 1-σ confidence level. Dose rate data are provided in the online supplement.